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State-of-Health Estimation of Lithium-Ion Batteries based on Partial Charging Voltage Profiles

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Different state-of-health (SOH) estimation methods for Lithium-ion batteries have been proposed in the literature. Even though these methods are showing good accuracy, they are developed for optimal laboratory conditions and do not consider various limitations, which are encountered in real-life applications. Therefore, in this paper, we proposed an alternative method for SOH estimation of NMC-based Li-ion batteries considering a reduced voltage interval for which the capacity fade is determined. For validation of the proposed SOH method, six different calendar aging cases have been considered.

Introduction

Lithium-ion (Li-ion) batteries have developed as the key energy storage solutions for various applications from power tools and consumers' applications to electric vehicles and renewable energy storage applications (1), (2). Besides offering better performance (e.g., high gravimetric and volumetric energy density, high power capability during both charging and discharging, long lifetime) in comparison to other energy storage devices (3), Lithium-ion batteries are non-linear systems with their performance and degradation behavior strongly dependent on the operating conditions (4), (5), (6). To benefit from the aforementioned advantages and to optimize the cost/cycle, knowledge about the battery state-of-health (SOH) has become mandatory for real-life applications. Consequently, the topic of Lithium-ion battery SOH estimation was brought at the forefront of the research.

Many battery SOH estimation methods have been developed and are available in the literature (7). These methods can be divided into experimental methods and adaptive methods (7), (8). The first group of methods relies on the direct measurement of certain battery parameters and use of their history to predict the battery SOH (9). The second group uses adaptive methods (e.g., Kalman Filters, Neural Networks, observers etc.) to quantify the battery SOH (10). Most of these methods, which show very good accuracy, are applicable and validated only for perfect laboratory testing conditions. However, in real-life applications, Li-ion batteries are subject to various constraints related to parameter estimation imposed by the battery management system (BMS). These constraints refer among others to impossibility of applying high current peaks to measure the internal resistance, discharge the battery to measure the capacity by other means then driving the car and/or have access to the whole battery voltage window, given by the manufacturer, in order to measure the battery capacity, as illustrated in Figure 1.

Thus, in this paper, we proposed a method for estimating the SOH (expressed as a function of capacity fade) of the battery, which focuses on the measurement of the battery charging capacity for a reduced voltage interval and not for the entire voltage window, between the minimum and maximum voltage, allowed by the manufacturer. Therefore, the hypothesis of this work is that the relative capacity fade defined for the entire voltage range is the same as for the reduced voltage range. Thereby, it is possible to estimate the actual capacity of a battery, based only on a reduced voltage range measurement.

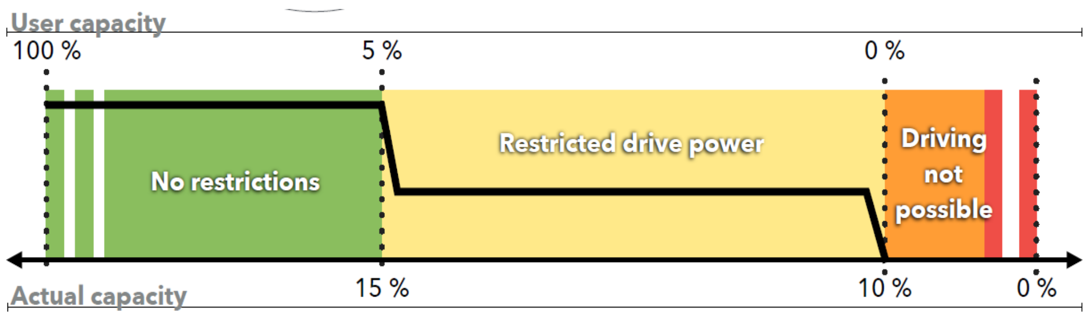

Figure 1. Difference between the actual capacity of the battery and the one available to the user in EV applications

Experiment

This work was performed considering 63 Ah NMC-based Li-ion battery cells, which are nowadays used in EV applications.

The NMC-based Li-ion battery cells were aged under the accelerated calendar aging conditions presented in Table I. As it can be observed, four different temperatures and three SOC levels were considered. The cells have been stored at open circuit condition, for 330 days; after every 30 days, a reference performance test was conducted at 25 ºC, in order to quantify the degradation of the NMC-based cells. During these periodic check-ups, the capacity, internal resistance, and small signal AC-impedance were measured.

TABLE I. Accelerated Calendar Aging Conditions

Temperature	**State-of-Charge**		
	10 %	50 %	90%
5 ºC		x	
35 ºC		x	
40 ºC		x	
45 ºC	x	x	x

Methodology

<u>Capacity Measurement</u>

The capacity of the NMC-based battery cells was measured using a constant current – constant voltage procedure, during both charging and discharging, for two consecutive cycles. The capacity, which was measured, during the second charging (see the highlighted in Figure 2), was used as a reference for investigation of the battery capacity fade and state-of-health estimation. Furthermore, in order to reduce the effect of the internal resistance, the capacity was measured using C/5-rate (i.e., 12.6 A).

The charging capacity of the battery is computed using the Coulomb counting method by integrating the battery current from the minimum to maximum voltage indicated by the manufacturer; in this case, the minimum voltage and maximum voltage are 3 V and 4.15 V, respectively.

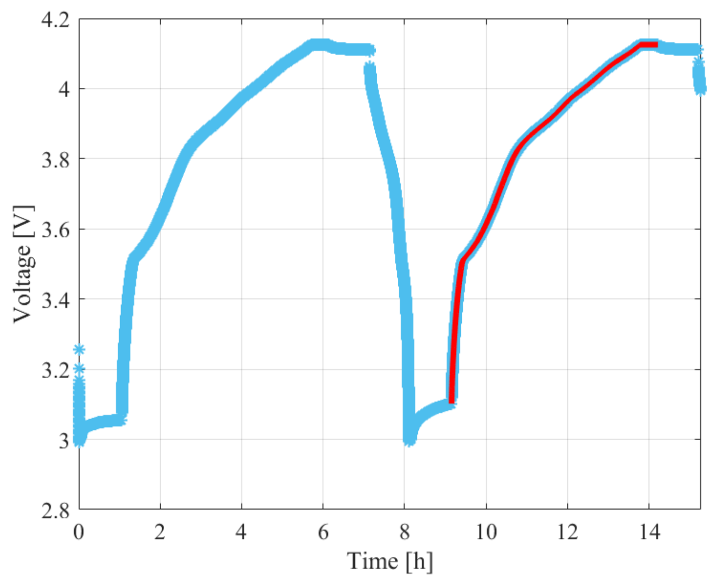

Figure 2. Voltage profile during capacity measurement (the voltage profile during the second charging capacity measurement is highlighted in red).

Capacity Determination for a Reduced Charging Interval

As it was already mentioned, in real life applications, it is rather impossible to measure the capacity of the battery between the minimum and maximum voltage level of the battery, which are given by the battery manufacturer. Furthermore, measuring the capacity between 0% and 100% SOC might return erroneous results, as at least one of the initial voltages (i.e., the voltages at the cell's beginning of life) corresponding to the minimum or maximum SOC levels will change during the battery life as the battery degrades. Therefore, we have evaluated the capacity fade behavior of the NMC-based cells for the cases when their capacity was measured for the following six voltage intervals: 3.5 – 3.8 V, 3.6 – 3.8 V, 3.8 – 3.9 V, 3.8 – 4.0 V, 4.0 – 4.1 V and 3.8 – 4.025 V. After performing an initial evaluation, the interval 3.8 V – 4.025 V, was selected for further investigation of the battery cells' capacity fade in this reduced voltage interval. An illustration of the selected voltage interval is presented in Figure 2. For a fresh NMC-based battery cell, the voltage interval 3.8 – 4.025 V corresponds to the 31 % – 72 % SOC interval, as illustrated in Figure 3.

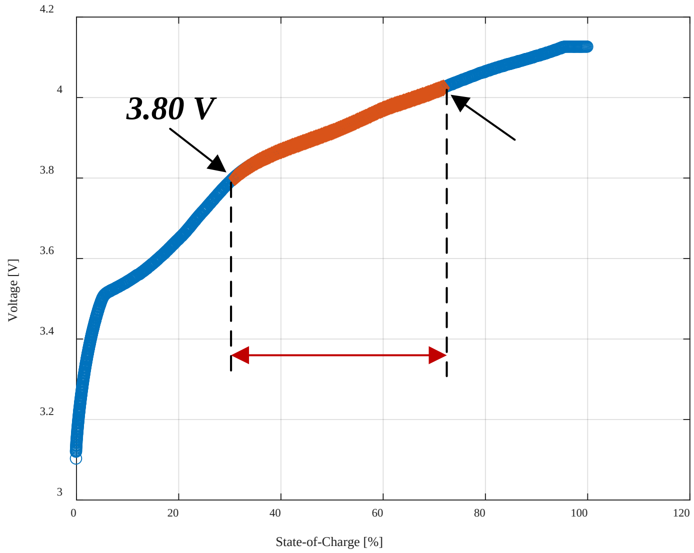

Figure 3. Comparison between the full and reduced voltage intervals used to determine the capacity of the NMC-based Li-ion battery cells.

Results

<u>Capacity Fade Comparison</u>

The evolution of the battery's charging voltage profile during calendar aging at 40ºC and 50% SOC, is presented in Figure 4. As one can observe, the shape of the whole voltage profile (Figure 4a) and of the selected voltage interval (Figure 4b) is changing only slightly during the 330 days of calendar aging, which caused a capacity fade of 19 %. Furthermore, during the aging process, a 3 % SOC shift was observed; after 330 days of aging, the selected voltage profile corresponded to the 28 % - 69% SOC profile.

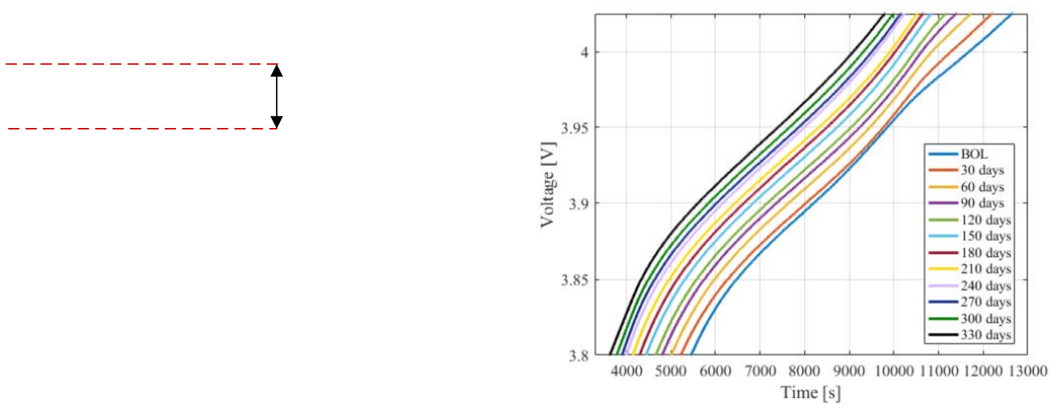

Figure 4. Evolution during calendar aging (40ºC and 50% SOC) of the charging voltage profile; a) whole voltage interval (3– 4.15 V), b) reduced voltage interval (3.8 – 4.025 V).

A comparison of the capacity fade trends, which were obtained for the two considered voltage profiles, for the six calendar aging cases, is presented in Figure 4.

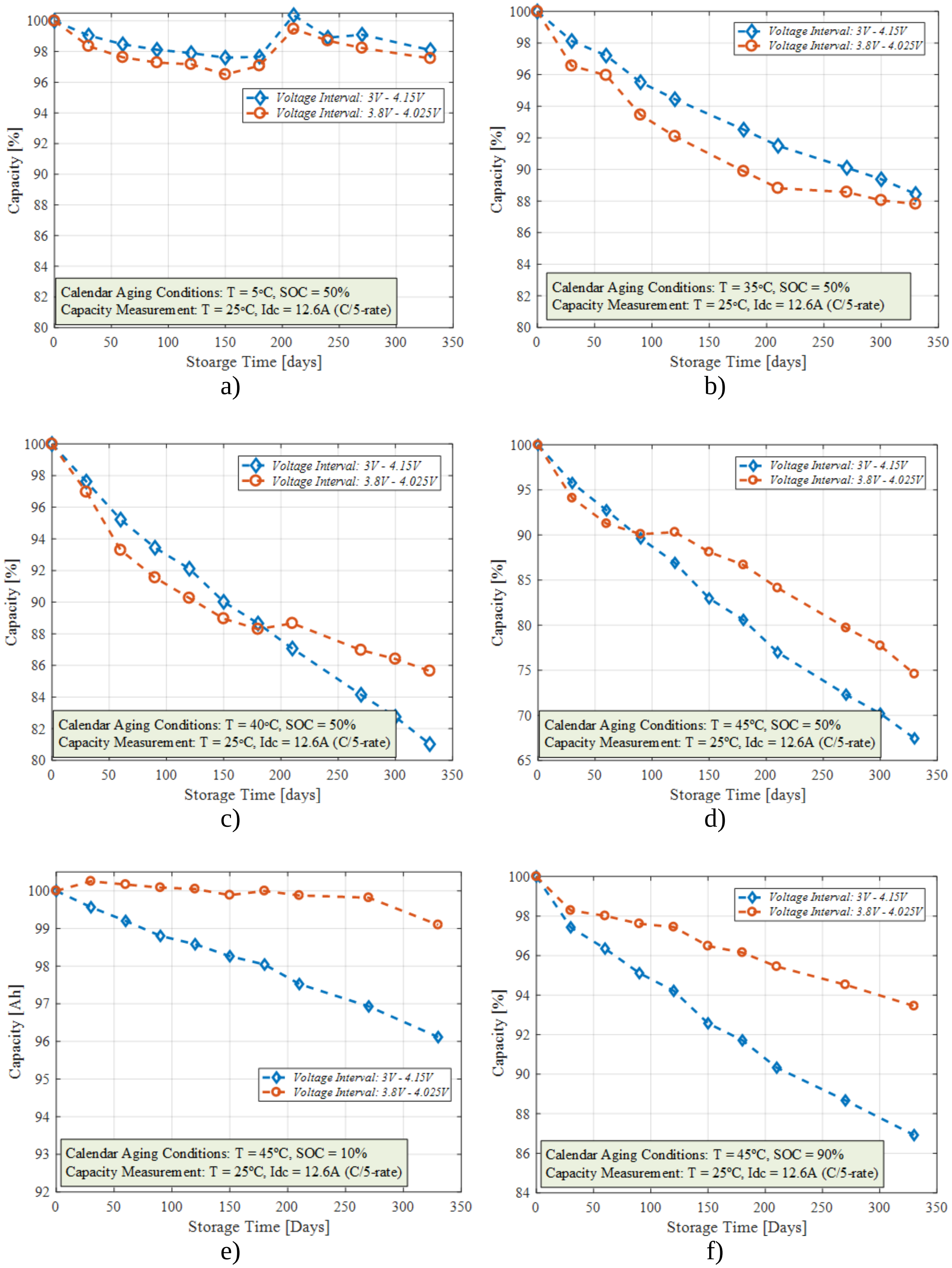

Figure 5. Comparison between capacity fade obtained for the whole voltage interval and for the reduced voltage interval at different calendar ageing conditions; a) T=5ºC, SOC=50%, b) T=35ºC, SOC=50%, c) T=40ºC, SOC=50%, d) T=45ºC, SOC=50%, e) T=45ºC, SOC=10%, f) T=45ºC, SOC=90%.

For the NMC-based Li-ion battery cells aged at 50 % SOC and various temperatures (Figure 5 a-d), a good agreement between the capacity fade trends obtained for both voltage intervals can be observed. For all these cases, until a degradation of approximately 12% is reached, the capacity fade calculated considering the reduced voltage interval overestimates the capacity fade calculated for the whole voltage charging; then, this trend is reversed.

Capacity Fade Estimation Error

Even though no consistent trends were obtained for the considered aging trends, the proposed SOH estimation method has an overall tendency to underestimate the capacity fade of the considered NMC-based battery cells, as visible from Figure 5. The capacity fade estimation error presented in Figure 6 was obtained according to [1].

$$\varepsilon = \text{Cfade\_all} - \text{Cfade\_red} \qquad [1]$$

Where, ε represents the capacity fade estimation error, Cfade_all represents the capacity fade determined for the case when the battery capacity is computed for the whole voltage interval and Cfade_red represents the capacity fade determined for the case when the battery capacity is computed for the reduced voltage interval.

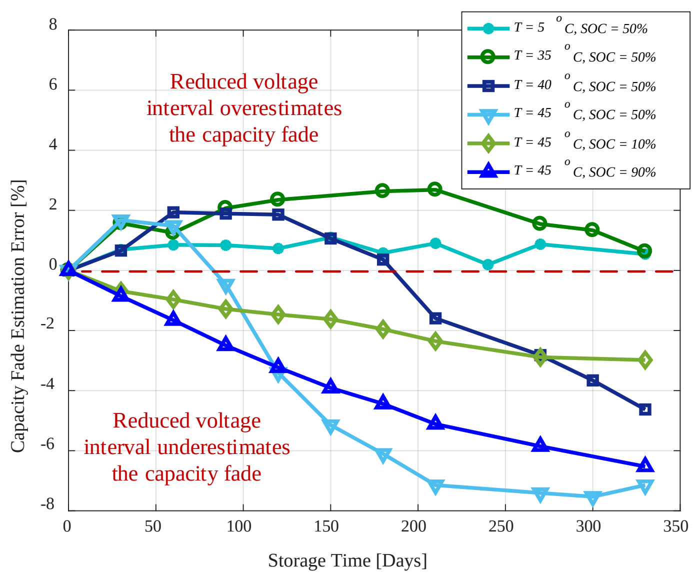

Figure 6. Estimation error of the capacity fade using the proposed method for all the considered aging cases.

For 330 days of calendar aging, which resulted into capacity fades varying from 2 % (aging at 5ºC and 50% SOC) to 32 % (aging at 45ºC and 50% SOC), the average capacity fade estimation error of the proposed method estimates is 2.25%. Moreover, as can be seen in Figure 7, higher capacity fade estimation errors were obtained for the case when an increased degradation (i.e., 12 – 15 % capacity fade) was measured on the NMC-based battery cells.

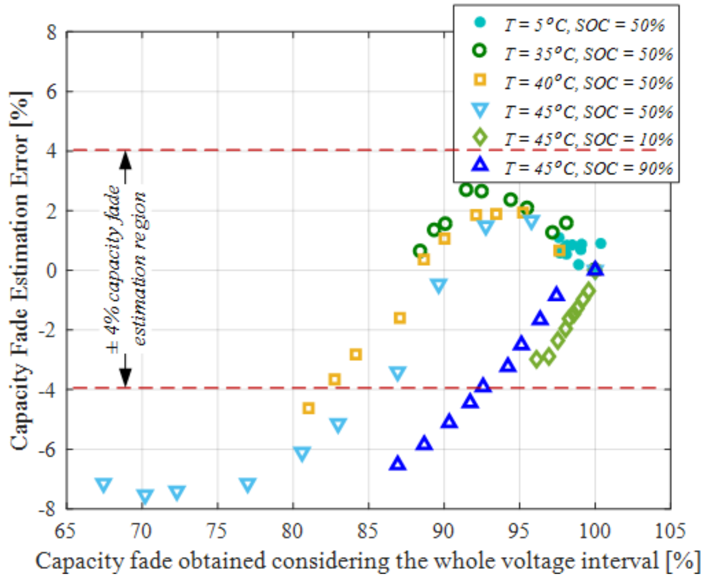

Figure 7. Capacity fade estimation error as a function of the capacity fade computed considering the whole charging voltage interval.

Conclusions

In this paper, an alternative method for SOH estimation of Li-ion batteries was proposed. The method relays on computing the battery capacity for a reduced charging voltage interval (i.e., 3.8 V – 4-025 V), and not for the entire voltage interval, which is specified by the manufacturer. To assess the method, NMC-based Li-ion batteries, which were specially manufactured for EV applications, have been tested at six different calendar-aging conditions for a period of 330 days. The obtained results have shown a relatively high accuracy of the proposed method, which was able to estimate the capacity fade of the tested battery cells with an average error below 2.5%. A higher estimation error of the capacity fade was obtained for increased degradation levels (i.e., higher than 12-15%) of the NMC-based battery cells; this behavior is believed to be caused by the increase of the cells' internal resistance, which causes changes in the voltage interval selected for capacity estimation.

Acknowledgments

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